LBL-12282
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Molecular Research Division

Submitted to the Journal of Fracture Mechanics

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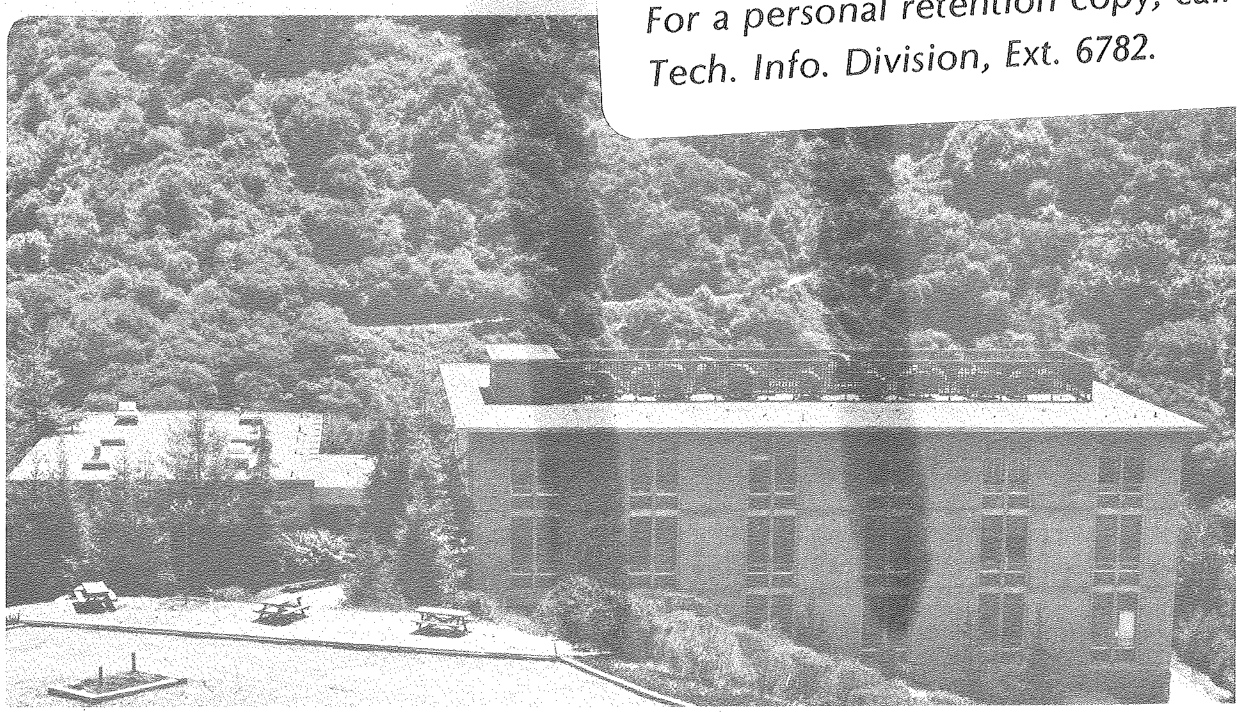
September 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

AN INVESTIGATION OF CORRELATIONS FOR PREDICTING MECHANICAL PROPERTIES OF "QUATOUGH" STEELS

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This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

The low-alloy medium carbon martensitic Fe/Cr/Mn/C system (called quatough steels) has been developed over the last decade at Berkeley with the intention of determining the optimum combination which would yield the best strength and toughness properties. From this development, a detailed investigation has been pursued in examining the role of microstructure in the area of mechanical properties and of the mechanisms involved by which high strength and toughness are obtained. As a result detailed correlations of microstructural relationships with mechanical properties have been obtained (see e.g. Refs. 1,2).

The present study focuses on the analysis of available mechanical data to investigate possible correlations between mechanical properties. For simplicity of analysis, all data chosen for this study are from steels with equivalent yield strength, ($\sigma \sim$ 180-200ksi), hardness ($R_C \sim 48 \pm 3$), and similar microstructure.[1,3-5] By keeping these parameters constant, it facilitates the investigation of whatever tentative correlations there might exist between some mechanical properties considered.

<u>Correlation between K_{1C} and E_{CV}</u>

It has been shown that many structural uses of steels of insufficient thickness do not exhibit plane strain behavior. Under such conditions, K_{1C} (plane strain fracture toughness) no longer provides an adequate and reliable measure of crack resistance. We shall denote such invalid data by K_Q. Therefore, care must be taken to satisfy the thickness constraint. Furthermore, because of the complexity and costliness of the plane strain toughness tests, it would be beneficial to be able to predict K_{1C} results by using a simpler method such as the Charpy V-notch test.

Some empirical correlations are already derived between E_{CV} and K_{1C} at room temperature. Barsom and Rolfe[6] and Groves and Wallace[7] have reported the following relationships for steels:

$$(K_{1C}/\sigma_Y)^2 = 5(E_{CV}/\sigma_Y) - 0.25 \qquad \text{B-R relation}$$

$$(K_{1C}/\sigma_Y)^2 = 2.786(E_{CV}/\sigma_Y) + 0.09 \quad \text{G-W relation}$$

Barsom and Rolfe[6] used 25.4mm (1 inch) thick specimens of wrought structural steel with yield strengths in the range from 110ksi to 250ksi. Some of the specimens in the region of lower strength range were too thin to provide valid values for the defined plane strain condition. On the other hand, Groves and Wallace[7] used 76.2mm and 127mm (3 to 5 inch) thick specimens of cast steel. The thickness of our specimens were identical to those used by Barsom and Rolfe. However, the strength of our steels all lie within a confined region of 180ksi to 200ksi, thereby avoiding many data which do not satisfy the plane strain condition. However, a number of such points (K_Q) still remain. Since these K_Q values for ductile specimens are invalid, we have resorted to calculating the K_{1C} value by the equivalent energy method described by Chell _et al._[8]. These will be denoted by K_{1C}^*. The existing data (K_{1C}- E_{CV}) from the Berkeley program are plotted and shown in Fig. 1. The resulting data points can be fitted to the following relationship:

$$(K_{1C}/\sigma_Y) = 0.0008(E_{CV}/\sigma_Y \cdot A)^2 + 0.3$$

where A is the cross-sectional area of a Charpy bar with value of $0.124 in^2$. Since the E_{CV} value in this equation is expressed in terms of in-lb (instead of the conventional ft-lb), the coefficient of this corresponding term therefore diminishes accordingly.

From the lower bounds of data in Fig. 1 (in dashed lines), the K_{1C} values can be conservatively estimated from the existing E_{CV} values. For the quarternary steels investigated in Berkeley, a specimen with an E_{CV} value of 35ft-lb will have a K_{1C} value of at least 93ksi $in^{1/2}$.

In Fig. 1, the curve inclines to the K_{1C} side, while Barsom-Rolfe, Groves-Wallace observed a curve inclined over to the E_{CV} side. It should be noted here that the materials chosen by Barsom-Rolfe, Grove-Wallace vary greatly in strength and hardness.

Much scattering of data is obvious in our curve, particularly the set of Carlson data[3] points which cluster in the lower region of the curve, display some independence of the E_{CV} value on variation of K_{1C} values. Nevertheless, this fluctuation will not affect the overall trend on a larger scale and can be ignored since these represent results from different heat treatment temperatures. Yet, whether other parameters are involved in this makeup is still rather uncertain.

The Ritchie[9] data for 4340 steels using different austenitizing temperatures at much higher yield strength are also included in the same figure. He points out that an inverse relationship exists between the E_{CV} and K_{1C} values. However, since the range occurs over a comparatively much smaller scale in contrast to our overall data examined, it cannot bring forth any contradiction to our hypothesis and the austeniziting temperature can only be regarded as a second order parameter for this kind of relationship.

<u>E_{CV} vs. Ductility</u>

Toughness is the ability of a metal to absorb energy and deform plastically before fracture. Toughness for a smooth tensile bar can be represented by the area beneath the conventional stress-strain curve and should be roughly proportional to the product of strength and elongation. Therefore, materials with the same yield strength level would be expected to exhibit a linear relationship between notch toughness and their elongation. However, from the present data, as shown in Fig. 2, there is no such correlation.

Such poor correlation between E_{CV} and elongation must be due to the appreciable fraction of plastic deformation concentrated in the necked region. Previous studies have used zero gauge length elongation which was converged from the reduction of area (zero gauge elongation $\equiv$ reduction of area/1-reduction of area) to represent the ductility near fracture. Here the E_{CV} values are plotted against the reduction of area (ductility) as shown in Fig. 3. In fact, the plot of E_{CV} vs zero gauge elongation shows almost the same result as E_{CV} vs reduction of area. Fig. 3 shows that the E_{CV} data are almost completely independent of the reduction of area at low and median ranges of ductility, whereas at the high ductility range (reduction of area larger than 45%), E_{CV} increases rapidly. This result would seem to suggest that factors other than just ductility are present which determine the Charpy V-notch toughness.

Notch Sensitivity (q_V) for a Charpy Bar

Ductility measurements on standard smooth tensile specimens do not always reveal metallurgical or environmental changes that reduce local ductility. This is the main reason why some tempered embrittlement phenomena were shown from the notch impact data but were not revealed from results of the tensile fracture test. The tendency for reduced ductility in the presence of a steep stress gradient which arises at a notch is called notch sensitivity. Conventionally, notch sensitivity was obtained by dividing the fracture strength of a notched specimen by that of smooth specimen. Here, however, for the purpose of using existing data, the notch sensitivity for a Charpy V-notch test under impact is defined as the ratio between the Charpy V-notch toughness energy and tensile fracture energy.

As mentioned earlier, the toughness for a smooth tensile bar can be obtained by simply measuring the area beneath the conventional stress-strain curve, and a rough estimate of the same could also be obtained by applying the following formula

$$\text{Tensile fracture energy } (E_T)$$

$$= \text{Elastic deformation energy + plastic deformation energy}$$

$$\simeq \left[\frac{\sigma_Y}{2} \times \varepsilon_e + \left(\frac{\sigma_Y + \sigma_{UTS}}{2}\right) \times \varepsilon_p\right]$$

$$= \left[\left(\frac{\sigma_Y + \sigma_{UTS}}{2}\right) \times \varepsilon_t - \frac{\sigma_{UTS}}{2} \times \varepsilon_e\right]$$

$$= \left(\frac{\sigma_Y + \sigma_{UTS}}{2}\right) \times \varepsilon_t - \frac{\sigma_{UTS}}{2} \times \frac{\sigma_Y}{E}$$

Thus tensile fracture toughness can be approximately estimated in terms of σ_Y (yield strength), σ_{UTS} (ultimate tensile strength), ε_t (total elongation) and Young's modulus, E. For high strength material, the calculated tensile fracture energy is quite close to that obtained by the area measurement method.

Since fracture is a localized phenomenon, and any geometrical change would inevitably change the local ductility drastically, it is therefore reasonable to regard notch sensitivity as a determining factor of fracture toughness as well.

The q_v values for Fe-4Cr-0.3C-XMn steels by different heat treatments and tempering conditions are shown in Fig. 4. Two clear drops in q_v value have been shown. The first drop corresponds to the tempered martensite embrittlement (TME) while the second drop shows the tempered embrittlement (TE). The origins of TME and TE have already been well discussed by other author[10]; the present result provides indication enough of the fact that the notch becomes more sensitive to fracture (i.e. reduced q_v value) when the material is tempered at 300°C and 500°C.

Fig. 5 regroups the data in Fig. 4 to reveal the effect of Mn addition on notch sensitivity at different heat treatments and tempering conditions. An increase in Mn concentration increases the q_v value (i.e. decreases the notch sensitivity) for $D_{200°C}$ (double heat treatment, tempered at 200°C), D_{AQ} (double heat treatment, as quenched) and $S_{200°C}$ (single heat treatment, 200°C tempered). This could be due to the fact that the addition of Mn effectively increases the amount of retained austenite which is believed, conventionally, to serve as a medium in blunting, branching out, and stopping cracks, thus reducing the notch sensitivity. However, in cases of S_{AQ} (single heat treatment, as quenched) and $S_{300-600°C}$ (single heat treatment and tempered at 300°C to 600°C), a decrease in q_v value is observed with an increase in Mn concentration. The cause of the drop in the q_v value for the $S_{300-600°C}$ case could be understood. The high Mn-concentration alloy has a higher percentage of retained austenite and therefore would produce a higher volume fraction of interlath carbides at 300-600°C tempering. These carbides enhanced crack initiation and propagation and increased the sensitivity of the notch (i.e. reduced q_v value). The case of the S_{AQ} is not easily explained by the reported microstructure, since the volume fraction of retained austenite also increases as Mn increases. However, one contradiction remains. If we explain the increasing trend of the double heat treatment by the increase in retained austenite, we should observe the same effect in the case of single heat treatment. It seems possible that other subtle microstructural changes which constitute the true cause of such phenomena might be obscured.

The relation between q_v value, Charpy V-notch toughness and ductility (reduction of area) is shown in Fig. 5. Fig. 5 is similar to Fig. 3, except that Carlson's[3] data are no longer included. This is because necessary information is lacking for the q_V value. The lines of equal q_V are approximately parallel to each other with q_V decreasing with toughness for the same ductility, and q_V decreasing with increasing ductility for the same toughness. Fig. 5 has clearly shown that notch sensitivity plays an important and consistent role, and that a decrease in notch sensitivity and an increase in ductility are equally important in improving notch toughness.

<u>Summary</u>

This study has shown that reliable correlations can be made between complex mechanical properties since parameters such as yield strength, hardness, and microstructure were held constant.

Conventionally, ductility has been regarded as a major determining factor of toughness, but the present analysis reveals another parameter, namely, the V shape notch-sensitivity, which shows consistent correlation to Charpy V-notch toughness for the Fe/Cr/Mn/C steels. This finding opens up a new element which alloy designers can consider in the process of acquiring steel of desired toughness. Once again it is emphasized that the notch sensitivity defined in this paper is the ratio between two fracture parameters which differs from the conventional one, as mentioned

earlier.

Another important observation is that in the high range toughness region, since the K_{IC} vs. E_{CV} curve shoots up rapidly at a certain E_{CV} value, any exceeding E_{CV} value provides a safe guarantee of high K_{IC} value.

Acknowledgement

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

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Figure Captions

Fig. 1. Correlation between K_{Ic} and E_{CV} for quatough steels.

XBL8010-6195

Fig. 2. Correlation between E_{CV} and total elongation (%) for quatough steels.

XBL8010-6196

Fig. 3. Correlation between E_{CV} and reduction of area (%) for quatough steels.

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Fig. 4. The Charpy notch sensitivity (q_V) for quatough steels at different heat treatments and tempering conditions.

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Fig. 5. The Charpy notch sensitivity (q_V) for quatough steels with different percentage of Mn.

Fig. 6. The relationship between E_{CV} and reduction of area as a function of q_V (notch sensitivity).

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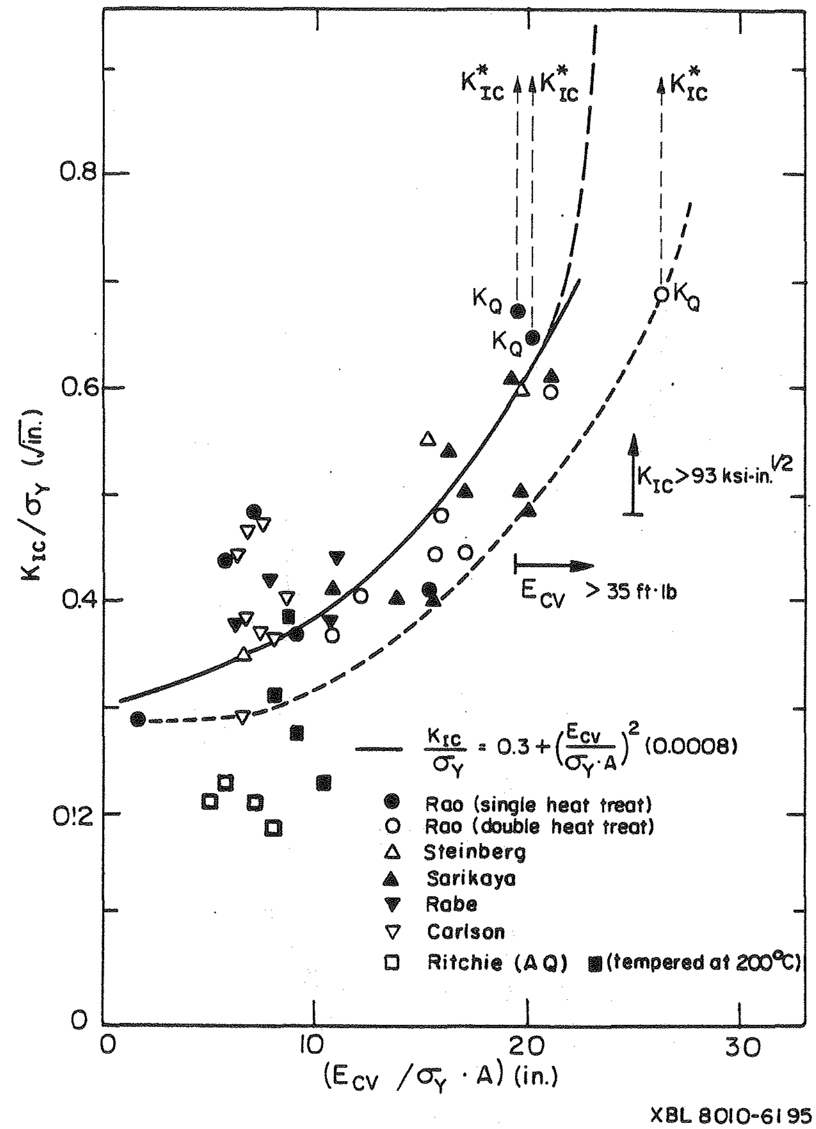
K_{IC}^*
K_{IC}^*
K_{IC}^*
K_Q
K_Q
K_Q
$K_{IC} > 93$ ksi-in.$^{1/2}$
$E_{CV} > 35$ ft·lb
$\frac{K_{IC}}{\sigma_Y} = 0.3 + \left(\frac{E_{CV}}{\sigma_Y \cdot A}\right)^2 (0.0008)$
Rao (single heat treat)
Rao (double heat treat)
Steinberg
Sarikaya
Rabe
Carlson
Ritchie (AQ)
(tempered at 200°C)
K_{IC}/σ_Y ($\sqrt{in.}$)
0.8
0.6
0.4
0.2
0
0
10
20
30
$(E_{CV}/\sigma_Y \cdot A)$ (in.)
XBL 8010-6195

Fig. 1

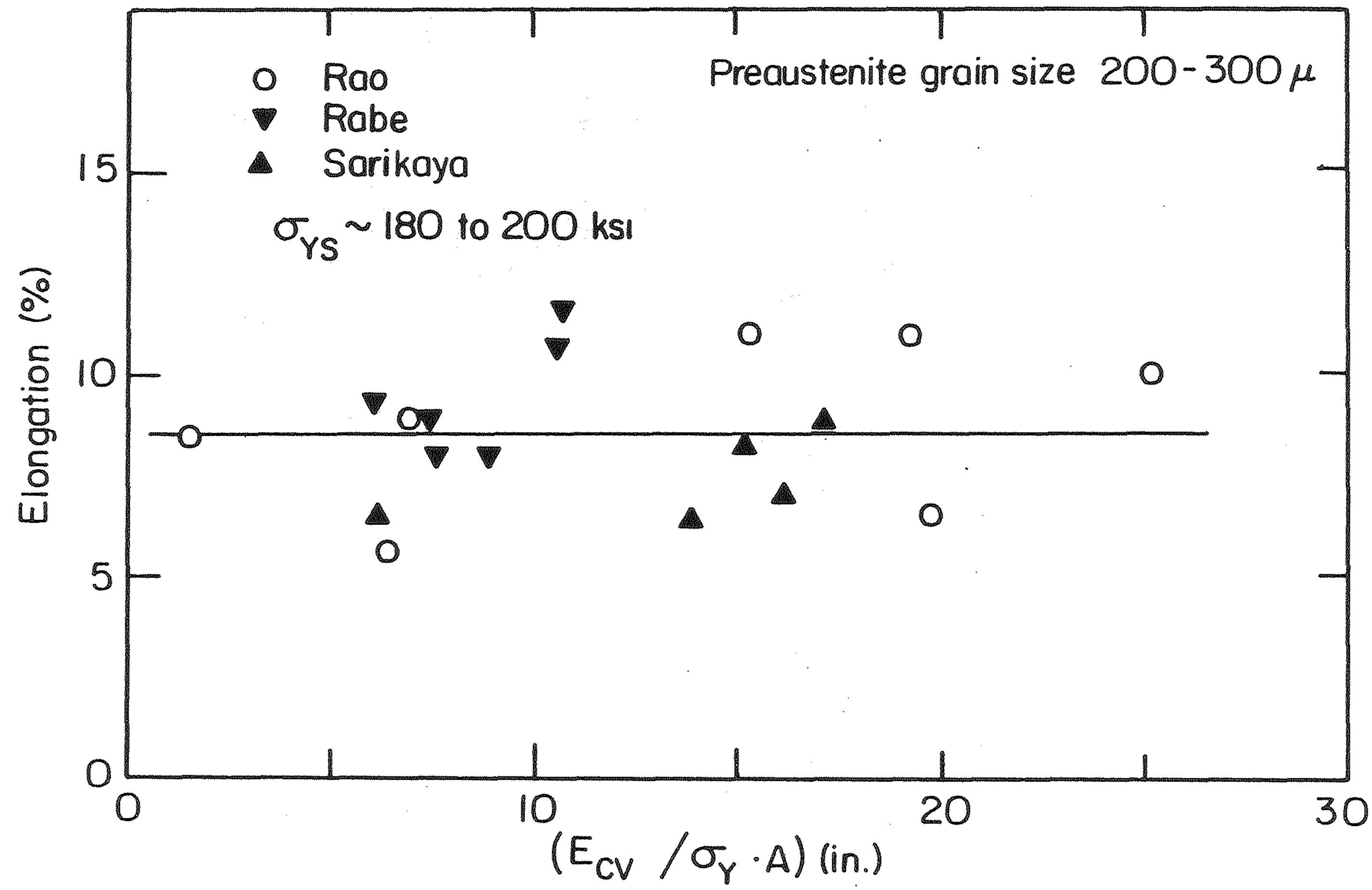

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Fig. 2

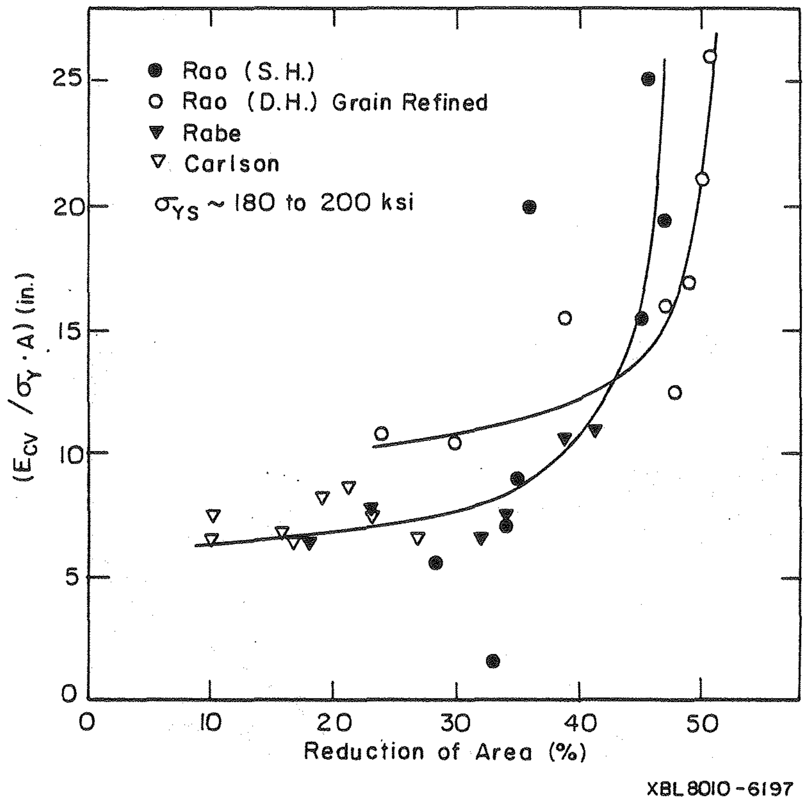
Rao (S.H.)
Rao (D.H.) Grain Refined
Rabe
Carlson
$\sigma_{YS} \sim$ 180 to 200 ksi
$(E_{CV}/\sigma_Y \cdot A)$ (in.)
Reduction of Area (%)
0
5
10
15
20
25
0
10
20
30
40
50
XBL 8010-6197

Fig. 3

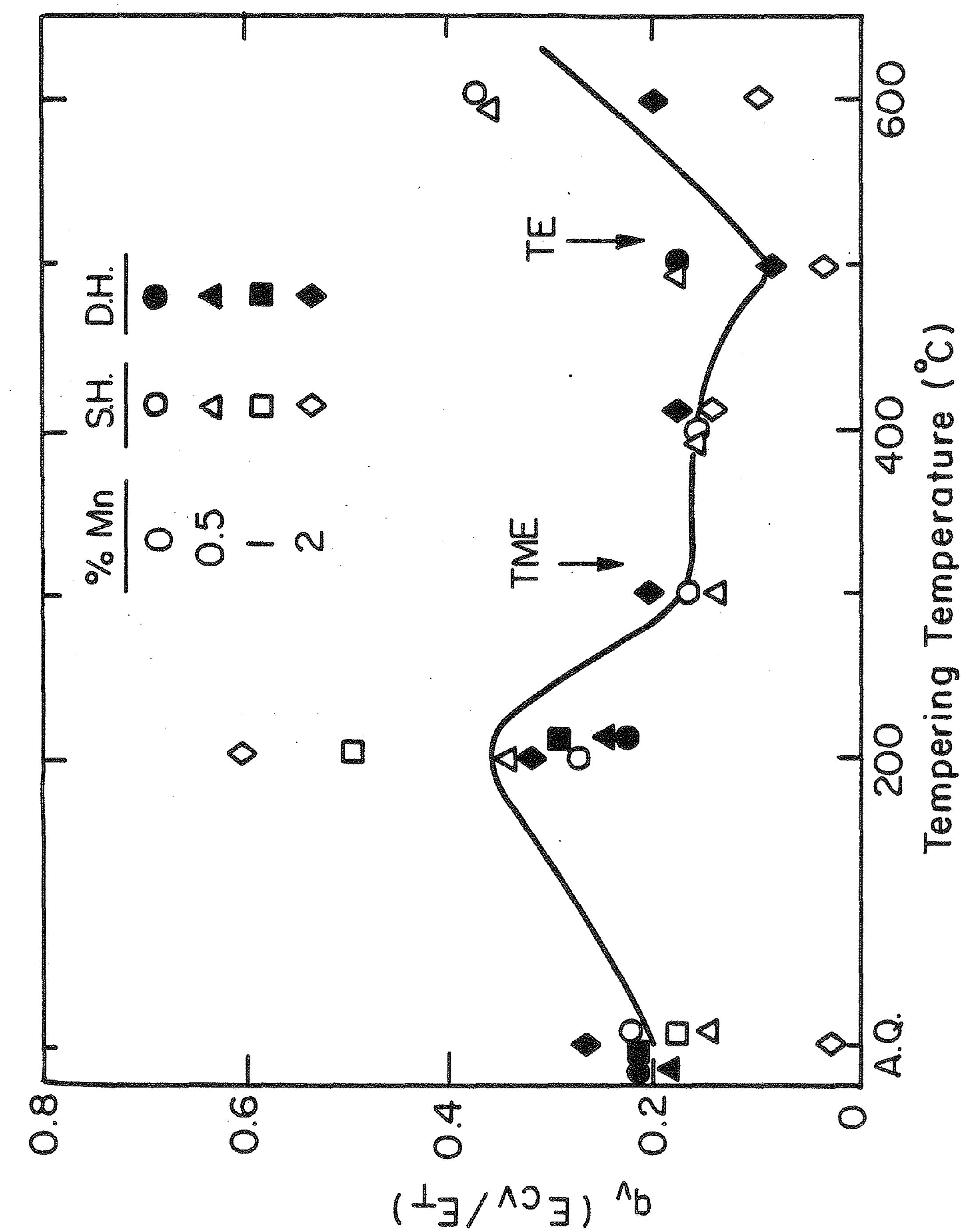

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Fig. 4

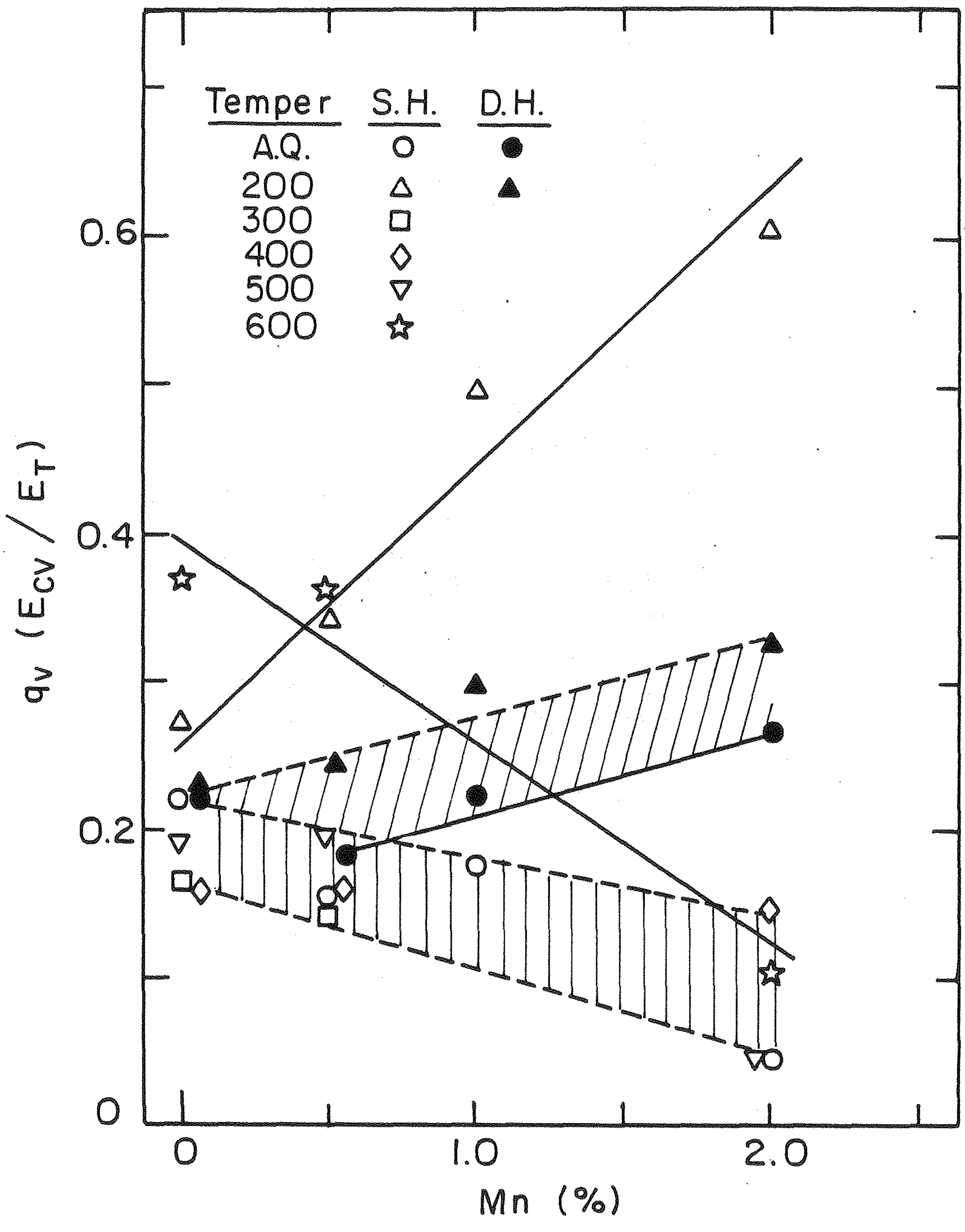
Temper
S.H.
D.H.
A.Q.
200
300
400
500
600
0.6
0.4
0.2
0
q_v (E_{CV} / E_T)
0
1.0
2.0
Mn (%)
XBL8010-6199

Fig. 5

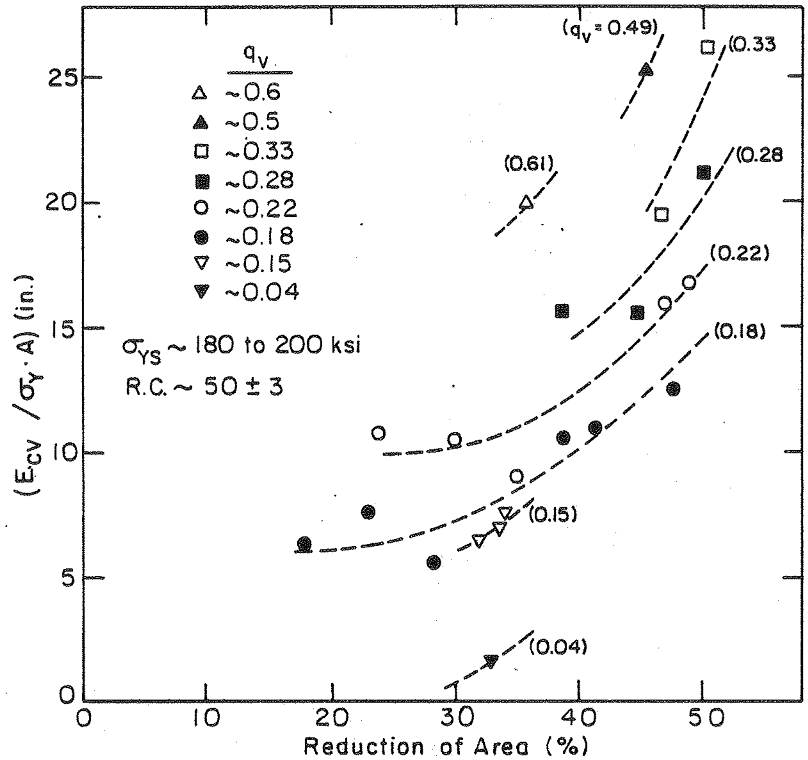

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Fig. 6